

Efficient Inversion in Underwater Acoustics with Iterative and Sequential Bayesian Methods

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LONG TERM GOALS

The long term goal of this project is to develop efficient inversion algorithms for successful geoacoustic parameter estimation and source localization, exploiting (fully or partially) the physics of the propagation medium. Algorithms are designed for geoacoustic inversion via the extraction features of the acoustic field.

OBJECTIVES

- Achieve accurate and computationally efficient geoacoustic inversion and source localization by designing estimation schemes that combine acoustic field modeling and statistical modeling.
- Develop methods for passive localization and inversion of environmental parameters that select features of propagation that are essential to model for accurate inversion.
- Implement sequential filtering methods that provide dynamic and efficient solutions for the first two objectives.

APPROACH

Continuing efforts from previous years, we work with Bayesian approaches applied to acoustic signals for the extraction of acoustic features using a combination of physics and statistical signal processing. We are focusing on identifying arrival times and amplitudes of distinct frequencies (within a single mode or across different modes). Those provide significant information on properties of the propagation medium and source location. The role of modal arrival times and amplitudes in geoacoustic inversion and source localization has been discussed in [1, 2, 3, 4, 5].

A method was developed by the PI and her research group in 2008 for modal decomposition of a received signal and modal arrival time estimation. The method employed principles of dynamical

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systems for multiple source tracking [6] and applied those to the extraction of “frequency trajectories” from spectrograms of received signals [7, 8, 9]. As also reported in previous years, every mode in the short time Fourier Transform (FT) representation of the signal is treated as a distinct source track with small changes in location (frequency, in our case) at each time step. We generated a particle filter that exploits two relationships, one for frequency updating vs. time (state equation) and the second one for comparison of the Fourier transform representation of a synthetic signal for the chosen state to that of the true signal (observation equation).

The method allowed the computation of posterior probability density functions (PDFs) for arrival times which can be used for uncertainty estimation in geoacoustic inversion.

To expand and improve on this work, we investigated how the observation equation of our filter can be improved and focused on specific snapshots of the spectrograms at specific times.

Similarly to [1] and [6], we employed in [10] Pseudo Wigner Ville representations to model acoustic signals in time and frequency [11], trying to improve the model of [1]. Time-frequency representations at selected times t were expressed as sums of shifted and scaled sinc functions with the help of the stationary phase approximation [1]. The centers and amplitudes of the sincs were related to modal frequencies and amplitudes. We then built a Gibbs Sampler to optimize the modal decomposition process, estimating arriving modal frequencies, corresponding amplitudes, and the number of modes present in the acoustic field.

We are currently comparing Pseudo Wigner Ville time-frequency representations to simple FT representations for performance evaluation in geoacoustic inversion. Figure 1 (a) demonstrates how the “sinc” approach works for FT spectra. A slice of the true spectrum is shown along with the Maximum a Posteriori estimate of the spectrum calculated with the Gibbs Sampler. As previously mentioned, the Gibbs Sampling method also allows the estimation of the number of modes present in an acoustic signal. Figure 1 (b) shows the probability density functions (PDFs) for the frequencies arriving at time t . Figure 2 shows preliminary inversion results, namely, the PDF for sound speed in the sediment for sound propagation in a synthetic shallow water environment.

In parallel, we explored how similar approaches can improve arrival time estimation; the ultimate goal is again accurate inversion, where the uncertainty in arrival times provides insight into the uncertainty in geometry/environment characterization. We developed and improved a particle filter-based approach where we jointly estimate arrival times at a set of hydrophones, taking into account possible variations of arrival times at spatially separated phones. This process allows us to substantially reduce the error in arrival time estimation and facilitates the calculation of probability distributions for these arrivals (which are not always Gaussian as often assumed in inverse problems). The developed approach has been applied successfully to real data from the SW06 experiment. Figure 3 shows time series recorded and the PDFs of arrival times. Density functions exhibit various levels of spreads, indicating that some arrivals are estimated with less uncertainty than others. The uncertainty can be employed in deciding which arrivals to use for inversion or how to weight (with large or smaller weights) particular arrivals.

WORK COMPLETED

The described estimation approaches were designed and applied to synthetic and real data. For the dispersion analysis, we worked initially with the Gulf of Mexico data (and synthetic data simulating

the Gulf of Mexico environment). The sound had propagated through a shallow water medium with a thin layer of sand over limestone; the frequency content of the signals was between 100 and 600 Hz. For the arrival time estimation of short-range multipath arrivals, we simulated signals received at a set of vertically separated receivers at a relatively small distance (~1000 m) from the source and used the Haro Strait data set. Additionally, the arrival tracking approach was applied successfully to Shallow Water 06 data for mid-frequency lfm sources. More tests are underway with all data sets.

RESULTS

Modal Arrival Estimation

Figure 1(a) shows a slice of the FT and the maximum a posteriori modal combination using the developed Gibbs Sampler. Figure 2(b) demonstrates the posterior PDFs for the arriving modal frequencies as computed via the Gibbs Sampler (the number of modes is also considered to be unknown). PDFs for different modes express different levels of uncertainty which are propagated into geoacoustic inversion.

Multipath Detection

Figure 4 demonstrates results from a particle filtering approach as applied to short-range time-series for arrival time estimation of distinct multipaths. The figure presents mean squared error in arrival time (in time samples) vs. number of particles for two different particle filtering techniques implemented here and compares this error to that from standard Maximum Likelihood (ML) estimation; two arrivals are estimated, direct and surface reflection. Arrival time error is much smaller with the dynamic methods, exploring spatial variability constraints across hydrophones. Performance is slightly better with the model labeled here as “velocity”, indicating that the rate of change of arrival time with space was taken into account in the dynamic relationship employed in our tracker. The gain in performance is more prevalent in lower Signal to Noise Ratios. Performance was further improved with smoothing techniques.

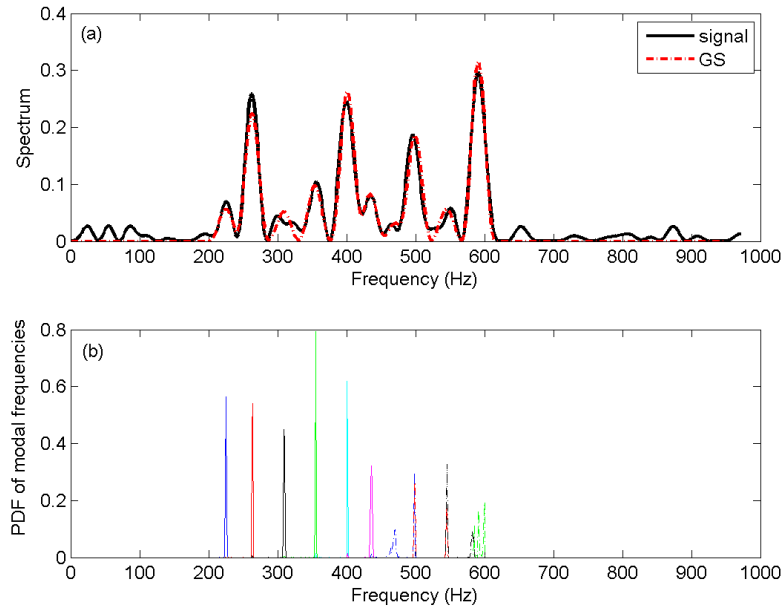


Figure 1: (a) A slice for a selected time t from the PSWVD of Figure 1 (red) and the MAP estimate for the modal decomposition as calculated by the Gibbs Sampler. (b) Posterior probability distributions of frequencies arriving at time t .

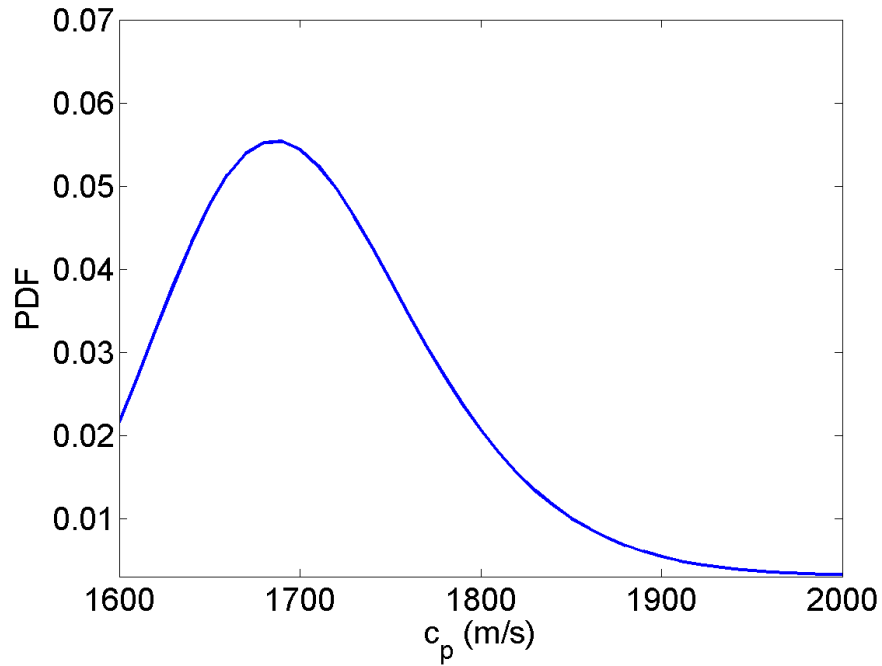


Figure 2: PDF of sound speed in the sediment for a synthetic shallow water environment

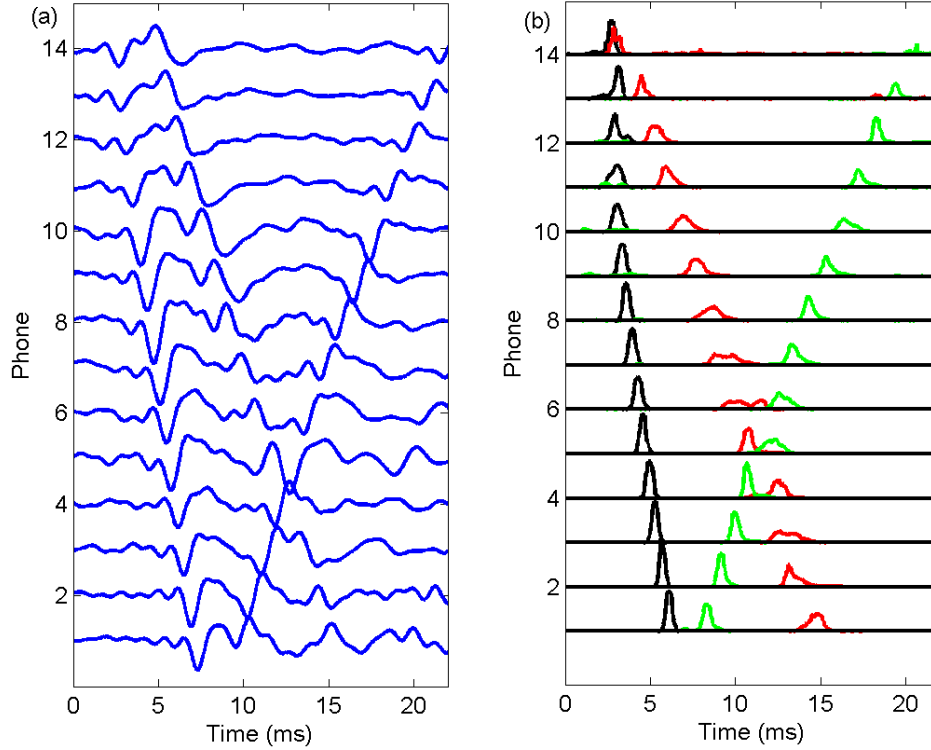


Figure 3: (a) Received time-series from lfm transmissions during the SW 06 experiment. (b) PDFs for arrival times of three paths calculated with particle filtering applied to the time series of (a).

IMPACT

The significance of accurate arrival time estimation in geoacoustic inversion has been extensively studied with several methods designed for producing geoacoustic parameter estimates and measures of the uncertainty in the estimation process. The reliability of these methods is intimately tied to the ability of accurately extracting and identifying arrival times. The new methods facilitate this extraction and the association between paths/modes and detected arrivals and also produce posterior probability distributions of modal frequencies or arrival times. These can then be employed to quantify uncertainty in the estimation of geoacoustic parameters as demonstrated in Figure 2.

RELATED PROJECTS

The PI is collaborating with Drs. Yardim and Gerstoft on sequential filtering in ocean acoustics [12]. A collaboration is also underway with Dr. Lisa Zurk (Portland State University) on tracking as it relates to the waveguide invariance principle [13]. Most of the work has so far been carried out with shallow water real data; in addition to tracking the invariance parameter was estimated and expressed using PDFs.

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HONORS/AWARDS

- Best Young Presenter Award in Acoustic Signal Processing for Rashi Jain (graduate traineeship award recipient), Meeting of the Acoustical Society of America, San Antonio, TX, October 2009.